

# The Square Kilometer Array: cosmology, pulsars and other physics with the SKA

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**ABSTRACT:** SKA is a new technology radio-telescope array, about two orders of magnitude more sensitive and rapid in sky surveys than present instruments. It will probe the dark age of the universe, just after recombination, and during the epoch of reionisation ( $z=6-15$ ); it will be the unique instrument to map the atomic gas in high redshift galaxies, and determine the amount and distribution of dark matter in the early universe. Not only it will detect and measure the redshifts of billions of galaxies up to  $z=2$ , but also it will discover and monitor around 20 000 pulsars in our Milky Way. The timing of pulsars will trace the stretching of space, able to detect gravitational waves. Binary pulsars will help to test gravity in strong fields, and probe general relativity. These exciting perspectives will become real beyond 2020.

**KEYWORDS:** galaxies; cosmology; pulsars.

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## 1. Main questions in Cosmology

We know now with great precision the content of the universe: with 70% dark energy, and 25% dark matter, the dark sector is dominating by far, while the baryons are only 5% of the total. However, the nature of these components is not yet known, and one of the main goals of future instruments is to determine their evolution in time, i.e. with redshift, to constrain their nature. Is the dark energy varying with time, or can it be reduced to a cosmological constant? Can we compare visible and dark matter at any redshift? Several missions, such as Euclid, or LSST, will gather data on billions of galaxies to trace with precision the evolution of the dark sector. SKA can bring complementary data in tracing as many galaxies at other wavelengths.

How is the Universe re-ionized? By mapping the neutral gas in its 21cm fundamental line, redshifted in the meter range, SKA will be unique to answer with high sensitivity and spatial resolution. The observations will cover the end of the dark age: cosmic dawn with line absorption, and Epoch of Reionization (EoR) with line emission.

How do baryons assemble into the large-scale structures? The observations of the atomic gas reservoirs at high redshift, which are not yet available, will considerably enlight galaxy formation

and evolution, the relative role of mergers or cold gas accretion in mass assembly, the star formation history and quenching, the role of environment in galaxy groups and clusters.

Black hole growth is accompanying closely bulge growth through star formation. It is likely that black holes and bulges compete for feeding, but also that implied nuclear activity (AGN) moderate or quench star formation through outflows, which will be studied at all redshifts.

Strong-gravity will be probed around pulsars and black holes. The discovery of thousands of new pulsars and their timing will provide a gravitational wave telescope.

## 2. How to probe the content and evolution of the universe

Looking far away with sensitive telescopes, it has been possible to look back in time, almost through the 13.8 billion years of its existence. The succession of events is now well known: following the hot Big-Bang, the plasma recombines 370 000 yrs after, and then begins the dark age, when there is no star yet to shine. Progressively, the baryons fall into galaxies and the gas collapses to form stars, whose UV light re-ionizes patches of universe around them. The epoch of re-ionization is expected to last between 0.5 and 1 billion years. Although active nuclei powered by super-massive black holes already exist and provide ionizing photons, the most likely agents of the re-ionization of the universe are stars in galaxies. After this cosmic renaissance, galaxies evolve and assemble mass, through accretion and hierarchical merging. Large scale structures up to galaxy clusters progressively emerge, and their precise growth rate will probe possible gravity laws modified beyond general relativity.

What is the fate of our universe? The standard candles SNIa have revealed the acceleration of expansion. Some of the best results on these tracers come from the 2003-2008 SNLS survey, a French-Canadian collaboration on the CFH telescope (about 500 SNIa, Sullivan et al. 2011, Conley et al. 2011, Betoule et al. 2014). Assuming a flat universe, it was possible to constrain values of the matter density  $\Omega_m$  and the parameter  $w$  from the equation of state of the dark energy:  $P=w\rho$ . The value  $w = -1$  compatible with a cosmological constant is still one of the most likely, within a 6% error bar.

When all the indicators are taken into account together, the supernovae Ia, the cosmic microwave background (CMB), the weak lensing and the baryonic acoustic oscillations for the large-scale structures, the concordance model begins to constrain more parameters of the dark energy equation of state  $P=w\rho$ . The  $w$  parameter is developed in  $w(a) = w_0 + w_a(1 - a)$ , where  $a$  is the expansion radius, normalised to 1 at  $z=0$ . Before Planck, Kowalski et al. (2008) found a weak evolution with redshift possible, while there is no evidence for a dynamical dark energy with Planck data (2014).

However, the CMB gives only an instantaneous view of the universe, 370 000 yrs after the Big Bang. The anisotropies measured in the CMB, coming from acoustic oscillations of photons and baryons together, provide a tremendous amount of data, on the curvature, the density of baryons, dark matter, and they already reveal some departures from the standard model predictions. For instance there are missing large-scale structures: there is not enough power at low spatial frequency (low- $l$ ) in the power-spectrum of the CMB signal.

To determine the evolution of dark energy, and therefore its nature, it is essential to measure the rate of expansion of the universe at any epoch. This can be done with the detection of baryonic

acoustic oscillations (BAO), at all redshift. The maximum size of these oscillations is well known, it is the sound horizon at the epoch of recombination, at  $t=370\,000$  yrs. The sound had time to run 150 Mpc, and the measurement of this size, then frozen in the comoving volume, in the power-spectrum of galaxies at any  $z$  will serve as a ruler to estimate the expansion rate.

## 2.1 BAO standard ruler

The first detection of BAO was done in the local universe by Eisenstein et al. (2005) with the Sloan spectroscopic survey, and in particular the luminous red galaxies (LRG). The region covered included about 47 000 galaxies, with redshifts between 0.2 and 0.5.

Already Alcock & Paczynski (1979) had proposed a simple way to probe the value of the cosmological constant, when galaxies are expanding in a ring structure: it is possible to compare the radius of the ring in the line of sight direction  $c\Delta z/H$ , and in the plane of the sky  $\Delta\theta D$  (where  $D$  is the angular distance). Since we are measuring the baryonic structures over the dynamics of the total matter, it will be possible to reach also the bias, i.e. to know how much the baryons trace or not the dark matter.

Today, there are many ongoing or future BAO surveys, like the Sloan BOSS, the DES or BigBOSS survey, Euclid, LSST projects and efficient reduction and reconstruction methods (e.g. Burden et al. 2014). All the surveys will be carried out in optical or infrared wavelengths. It is important that billions of galaxies could also be traced in a complementary way, with the atomic gas and the 21cm line. The biases will be different, for instance, HI-rich galaxies tend to avoid galaxy clusters, while the infrared surveys on the contrary are biased towards high surface-densities of galaxies.

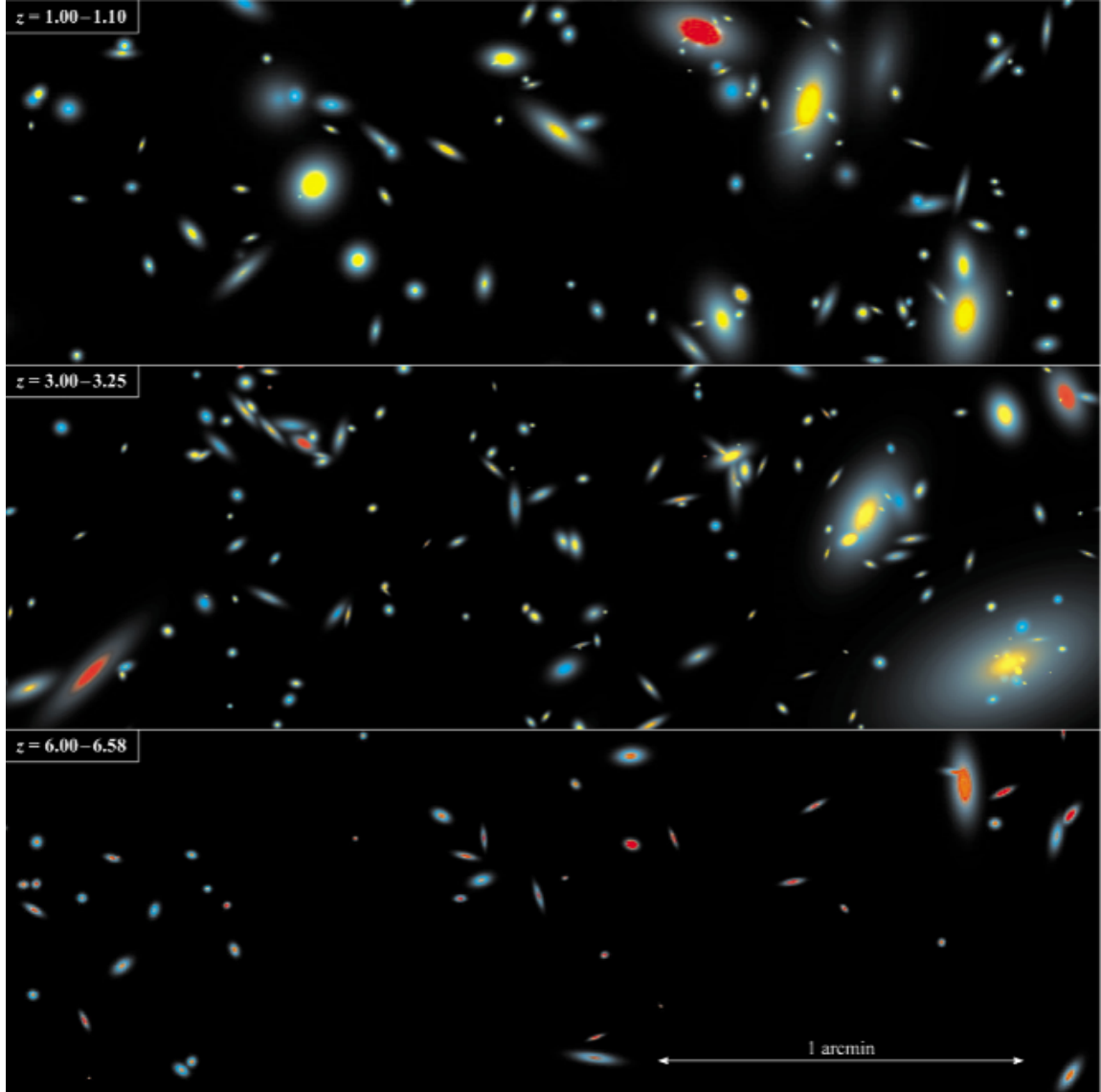
There are several ways that SKA can contribute significantly to the BAO surveys. The first phase SKA-1 can cover three types of surveys, differing by their depth: an all sky survey ( $3\pi$  sr), providing  $4 \times 10^6$  galaxies at  $z \sim 0.2$ , a wide-field survey ( $5000 \text{ deg}^2$ ) with  $2 \times 10^6$  galaxies at  $z \sim 0.6$ , and a deep-field survey ( $50 \text{ deg}^2$ ) with  $4 \times 10^5$  galaxies at  $z \sim 0.8$ . Alternatively, an intensity mapping can be carried out over  $25\,000 \text{ deg}^2$ , and will bring a competitive constraint on the expansion rate at  $z \sim 2$  (Bull et al. 2015). The second phase SKA-2 will be able to provide a redshift survey over  $30\,000 \text{ deg}^2$ , yielding much better results than other experiments, for redshifts up to 1.4.

The large galaxy redshift surveys foreseen with SKA will not only be useful for BAO, but also for other tools, like the Redshift Space Distortions (RSD), tracing peculiar velocities off the Hubble flow, either random (finger-of-god effect in galaxy clusters), or more coherent (infall of galaxies on clusters, Kaiser effect). Cross-correlation with the optical surveys, such as Euclid, will enrich the information (Abdalla et al. 2015).

About the weak shear tool, SKA can provide high-resolution continuum images of 10 billion galaxies.

## 2.2 Continuum surveys with SKA-1

In 2yrs of all-sky survey, the goal with SKA-1 is to achieve  $2 \mu\text{Jy}$  rms, which will allow to detect at more than  $10\sigma \sim 4$  galaxies per  $\text{arcmin}^2$ . The spatial resolution and the quality of the synthesized beam, will allow to measure the weak lensing, and the Integrated Sachs Wolfe (ISW) effect. With almost uniform sky coverage of  $3\pi$  sr, a total of 0.5 billion radio sources will be detected. In the



**Figure 1.** Simulated sky over a field of  $3 \times 1 \text{ arcmin}^2$ . From top to bottom are represented 3 different redshift ranges ( $z=1-1.10$ ,  $3-3.25$  and  $6-6.58$ ), with depth corresponding all to 240 Mpc. Blue colors indicate HI-21 cm line flux, and the orange-red colours to the CO line (molecular gas). From Obreschkow et al. (2009b).

wide-field ( $5000 \text{ deg}^2$ ) survey,  $\sim 6$  galaxies per  $\text{arcmin}^2$  can be reached above  $10\sigma$  with a  $2 \mu\text{Jy}$  rms, while in the deep-field ( $50\text{deg}^2$ ) with  $0.1 \mu\text{Jy}$  rms, this leads to  $\sim 20$  galaxies  $\text{arcmin}^2$ .

These numbers can be compared to the present status of radio surveys. In the Hubble deep field north, an area of  $5 \times 5 \text{ arcmin}$  has been observed during 50 hours, with the VLA by Fomalont et al. (1997); 6 sources were detected with a flux at 8.4GHz larger than  $> 12 \mu\text{Jy}$ .

Radio-galaxies are of different types, the brightest are AGN (active nuclei), but they can also be ordinary star forming galaxies or starbursts. These large surveys will reveal how they trace the bulk of the mass at any redshift. In any case, the bias of these sources, the way they trace the dark matter distribution, will be quite different than for optical/infrared surveys (Jarvis et al. 2015).

Brown et al. (2015) have shown how SKA will bring new perspectives to weak-lensing surveys, using polarization and rotation velocity to disentangle intrinsic alignments, and extend studies at high redshift.

Simulations of the sky at radio wavelengths have been computed by Jackson (2004), Obreschkow et al. (2009), at different redshifts, and including the main lines of HI and CO (see figure 1).

### 2.3 Radio relics, radio halos

Radio emission at Mpc scales are often observed in galaxy clusters, and are a precious information on the cluster physics, relaxation state and magnetic fields. Radio relics are formed as shocks during a cluster merger, to form a more massive galaxy cluster (e.g. Van Weeren et al. 2012). They are elongated and irregular structures, such as in Figure 2, which shows a radio relic in the form of a tooth brush. In a shock, charged particles are accelerated to relativistic energies. In the presence of magnetic fields, they radiate synchrotron radiation. The observations reveal large-scale alignment of magnetic field, and a strong spectral index gradient.

Radio halos are also diffuse radio emission extending at Mpc scale, associated to cluster mergers, but unpolarised, and located at the center of the clusters. They have a more regular morphology than radio relics which are often found at the borders of clusters, and are highly polarised.

Giovannini et al. (2015) explore how SKA-1 will be able to detect diffuse radio emission in low density regions, tracing intergalactic filaments, in galaxy groups and clusters, and tackle the evolution of cosmological magnetic fields.

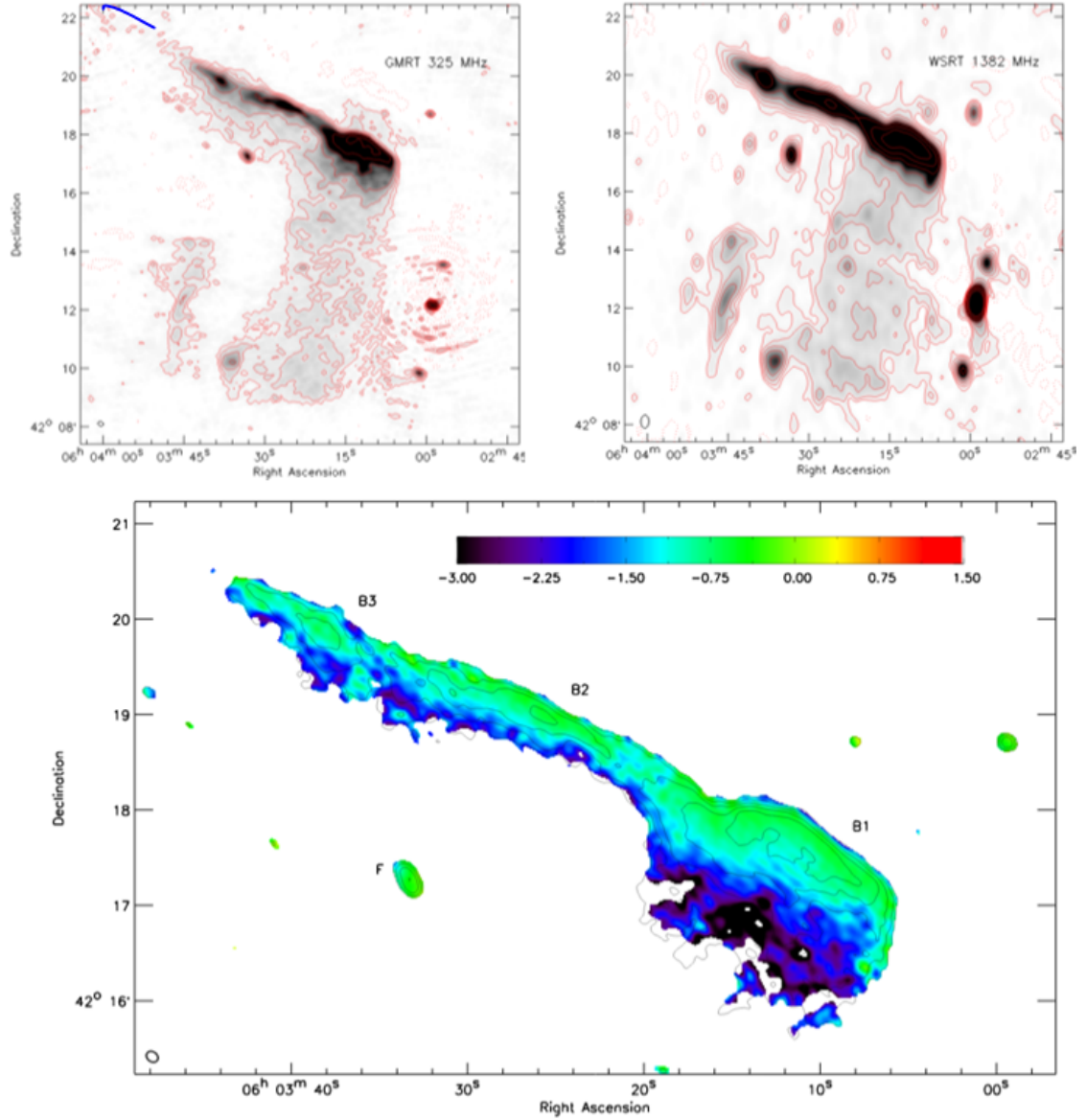
## 3. Epoch of Reionization

The SKA is unique to observe the HI-21cm fundamental line redshifted at very high redshift, up to  $z=20-30$ . This means that the formation of the first stars and galaxies will be explored, through the intergalactic medium, which is mostly neutral atomic hydrogen, until the end of re-ionization at  $z\sim 6$ . The UV light from the first stars are ionizing their surroundings, and numerical simulations have shown how the various ionized patches inflate, and lead to a progressive percolation of ionized zones (e.g. Iliev et al. 2006, Baek et al. 2009).

Since the gas kinetic temperature falls down in  $(1+z)^2$ , while the CMB temperature varies as  $(1+z)$ , the gas is first colder than the radiation. However the excitation temperature ( $T_{spin}$ ) is equal to the kinetic temperature only when the medium is dense enough (dark age), or pumped by Lyman- $\alpha$  photons (cosmic dawn). Without efficient excitation,  $T_{spin}=T_{CMB}$ , and it is impossible to see any absorption or emission signal (see figure 3). Later on, the gas is heated by the star formation, and the signal will be seen in emission in the EoR.

Up to now, the EoR signal has not been detected. Only simulations have been able to estimate the expected signal. Although the predicted signal is strong enough to be observed by present telescopes, the foreground emissions are at least 4 orders of magnitude higher, and are not easily disentangled. They will remain a challenge for SKA (Chapman et al. 2015).

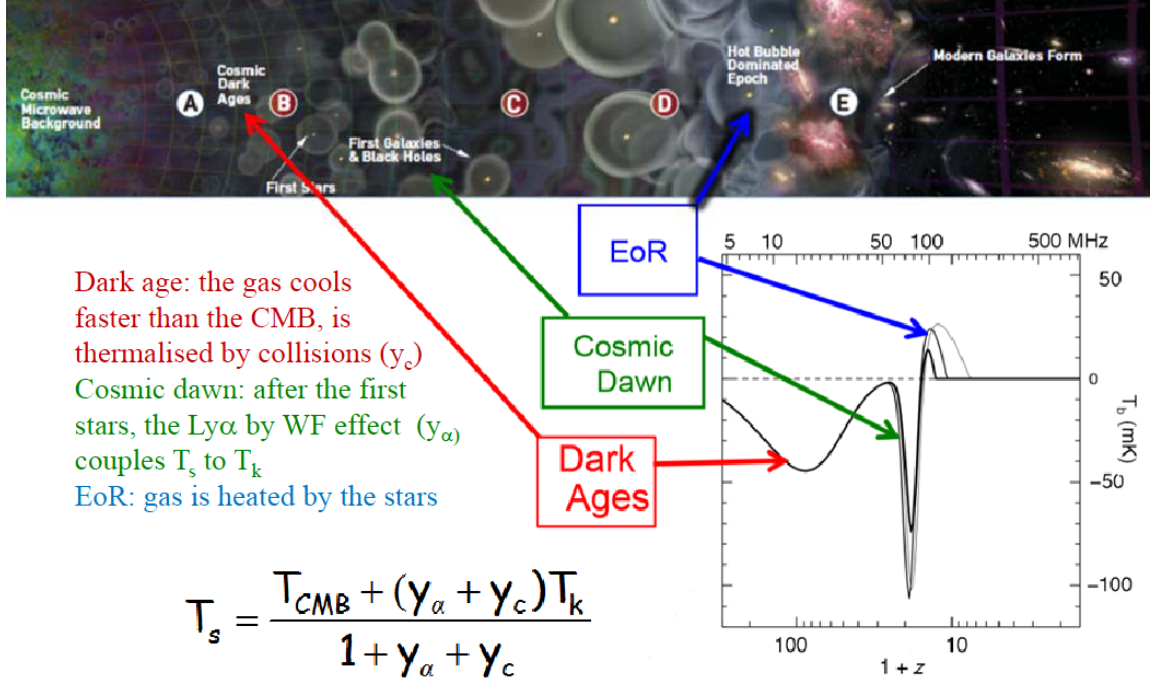
Mellema et al. (2015) describe how HI tomography with SKA-Low is essential to characterize the Cosmic Dawn (CD) and Epoch of Reionization (EoR). Path finder instruments, such as GMRT, MWA, PAPER and LOFAR are able to provide only power-spectrum of the signal, but imaging at a given redshift, or make real cubes of data, will be the privilege of SKA.



**Figure 2.** **Top** At left is the GMRT 325 MHz map of the merging cluster 1RXS J0603+4214, at  $z=0.225$ . At right, the 1382 MHz map, taken with WSRT. **Bottom** The colors reproduce the index of the emission from GMRT between 610 and 325 MHz (see the color palette at the top), and the contours are from the GMRT 325 MHz image. Adapted from van Weeren et al. (2012).

Another way to explore the EoR is to image the surrounding of  $z>6$  quasars, and the ionized patch in their environment (Geil & Wyithe 2008). These observations will be complementary to those in the optical or infrared with JWST and ELT, detecting the HII regions around high redshift QSO. Also absorption studies will focus on the 21cm forest, in analogy to the Lyman- $\alpha$  one (Ciardi et al. 2015).

Since the observation by Planck of a Thompson optical depth significantly lower than previously thought, it becomes clear now that the first galaxies from  $z\sim 10$  until  $z\sim 6$  are perfectly able



**Figure 3.** Succession of events, from the Big-bang at left, to the EoR (Epoch of Reionization) at right, during the first billion years of the Universe. In the first phase, the dark ages, collisions are still strong enough to couple the spin (excitation) temperature of the H-atoms to the kinetic temperature of the gas, which decreases in  $(1+z)^2$ , faster than  $T_{CMB}$  in  $(1+z)$ . The expansion of the universe reduces the collision strength, and the H-atoms spin temperature progressively aligns with  $T_{CMB}$ . Then the first stars light up, and emit Lyman $\alpha$  photons, which couple the H-atoms to their kinetic temperature again, through the Wouthuysen-Field effect (WF). This is the cosmic dawn, and the HI-21cm signal can be detected in absorption. When stars are progressively more numerous, the gas is in majority heated by their radiation, and the 21cm signal can be detected in emission. Adapted from Pritchard & Loeb (2010).

to re-ionize the universe (e.g. Bouwens et al. 2015). The detailed HI tomography will allow to follow the evolution and growth of these galaxies.

#### 4. Galaxy formation and evolution

HI-21cm mapping in galaxies is a unique tool to determine through the rotation curve the dark matter distribution in galaxies. Up to now, this has been possible only in the local universe, by lack of sensitivity. With SKA, this will be possible up to  $z=5$ , and the evolution of the ratio between baryons and dark matter will be known through cosmic time. This will help to solve one of the main problem in galaxy formation and evolution: why are there so few baryons in galaxies? In the local universe, the baryon fraction maximizes at 20% of the universal baryon fraction, in galaxies of the Milky Way type, of total mass of  $\sim 10^{12} M_\odot$ . The baryon fraction is even much lower in dwarf and massive galaxies. When do galaxies lose their baryons? or were the baryons never accreted in galaxy haloes?

In addition, HI is the fundamental reservoir for star formation and black hole growth, before it is transformed in the molecular phase, at high density in the galaxy centers (Leroy et al. 2013). The



observation of the neutral gas with high resolution up to  $z=2$ , corresponding to the peak of activity in the star formation history, will help to answer fundamental questions such as: How galaxies assemble their mass? How much mass assembled in mergers? How much through gas accretion and secular evolution?

In the recent years, cold gas accretion from cosmic filaments have been promoted as the main motor of evolution. Most stars in the universe have been formed while galaxies are in the main sequence, and only of the order of 10% in a starburst mode. However, the quenching mechanisms have not yet been identified, although star formation and AGN feedback are suspected. The SKA mapping of the morphology and kinematics of the neutral gas will identify inflows and outflows of gas, and thie evolution with redshift (Blyth et al. 2015).

## 5. Black holes in galaxies

It is well established now that each galaxy hosts a supermassive black hole in its center, which mass is about  $1-2 \cdot 10^{-3}$  of the bulge mass. This proportionality has been explained by the star formation moderation exerted by the AGN activity. Several mechanisms have been invoked for this feedback action, in particular radio jets could be efficient enough (Wagner et al. 2012). Recent observations have revealed the existence of massive molecular outflows around active nuclei (Feruglio et al. 2010, Ciccone et al. 2014). The rate of outflows can be as high as 1-5 times the star formation rate, meaning that the star formation is indeed reduced.

One environment where the AGN feedback is obvious is galaxy clusters, and in particular cool core clusters. In most of them, a radio-loud AGN is hosted by the Brightest Cluster Galaxy (BCG), whose jets dig cavities in the hot X-ray emitting plasma (Fabian et al. 2003). In the prototypical example, the Perseus cool core cluster, cold molecular gas has been detected around the cavities, corresponding to the expected cooling flow (Salome et al. 2006). Instead of cooling towards the center, as in the simplistic model, the gas is cooling at 20-30kpc from the BCG center, and falls along filaments, that are conspicuous in  $H\alpha$ . Radio continuum emission gives important information about filaments and magnetic fields. This work can be done at much higher redshift with SKA.

Not all black holes have been seen. According to the proportionality relation between bulges and black hole masses, there should exist intermediate-mass black holes (IMBH) in dwarf galaxies, or may be in the outer parts of galaxies, since they are not massive enough to spiral into their galaxy nucleus. One candidate of such an object is the ultra-luminous X-ray source HLX1, discovered as a companion of the edge-on early-type spiral ESO 243.49, at 95 Mpc distance. The energy of the X-ray source, of  $10^{42}$  ergs/s is difficult to explain with binary stars, and must come from a black hole of mass  $10^2-10^5 M_{\odot}$  (Webb et al. 2010). With SKA, the search for IMBH could be more successful.

Smolcic et al. (2015) explore the possibilities opened by SKA and its various sky surveys in detecting radio-loud and radio-quiet AGN as a function of cosmic time. The question of bimodality between these two categories might find a solution, in the evolution of quasars between these two phases, or in different emission mechanisms. The black-hole accretion rate, and its cosmic history will be established on solid grounds, together with the AGN role on quenching star formation in galaxies.

## 6. Pulsars

Pulsars are rotating neutron stars, discovered by Bell & Hewish (1968). They are the life end of massive stars, after their explosion in supernovae, if their core is not massive enough to form a black hole. Their size is of the order of 10km, and their mass 1-2  $M_{\odot}$ , so their central density is larger than that of atom nuclei, of the order of  $10^{15}\text{g/cm}^3$ ! The gravity at their surface is  $\sim 10^{11}\text{ g}$ , and their magnetic field up to  $B=10^{12}\text{ Gauss}$ .

Up to now, 2000 'normal' pulsars are known in the Milky Way. Their rotation period is usually on the scale of one second (the Crab pulsar has a period of 0.03s), acquired just after SN explosion. But there exists a category of milli-second pulsars (MSP), which have been re-activated in X-ray binaries.

Alone the pulsar can live 100Myr, losing energy through multipole radiation. But in a binary, the companion can transfer mass and angular momentum when in the giant phase, accelerating the pulsar. Since the magnetic field  $B$  is down to  $10^8\text{G}$ , the spinning can live during Gyrs.

Pulsars are exceptional clocks, that can be measured with extreme precision. The discovery of binary pulsars (Hulse & Taylor 1975) and their timing has already indicated the existence of gravitational waves (Nobel prize in 1993), since the binary loses energy through emission of these waves. From the high precision clock and its Doppler effect in the binary orbit, it has been possible to measure the shrinking of the orbit.

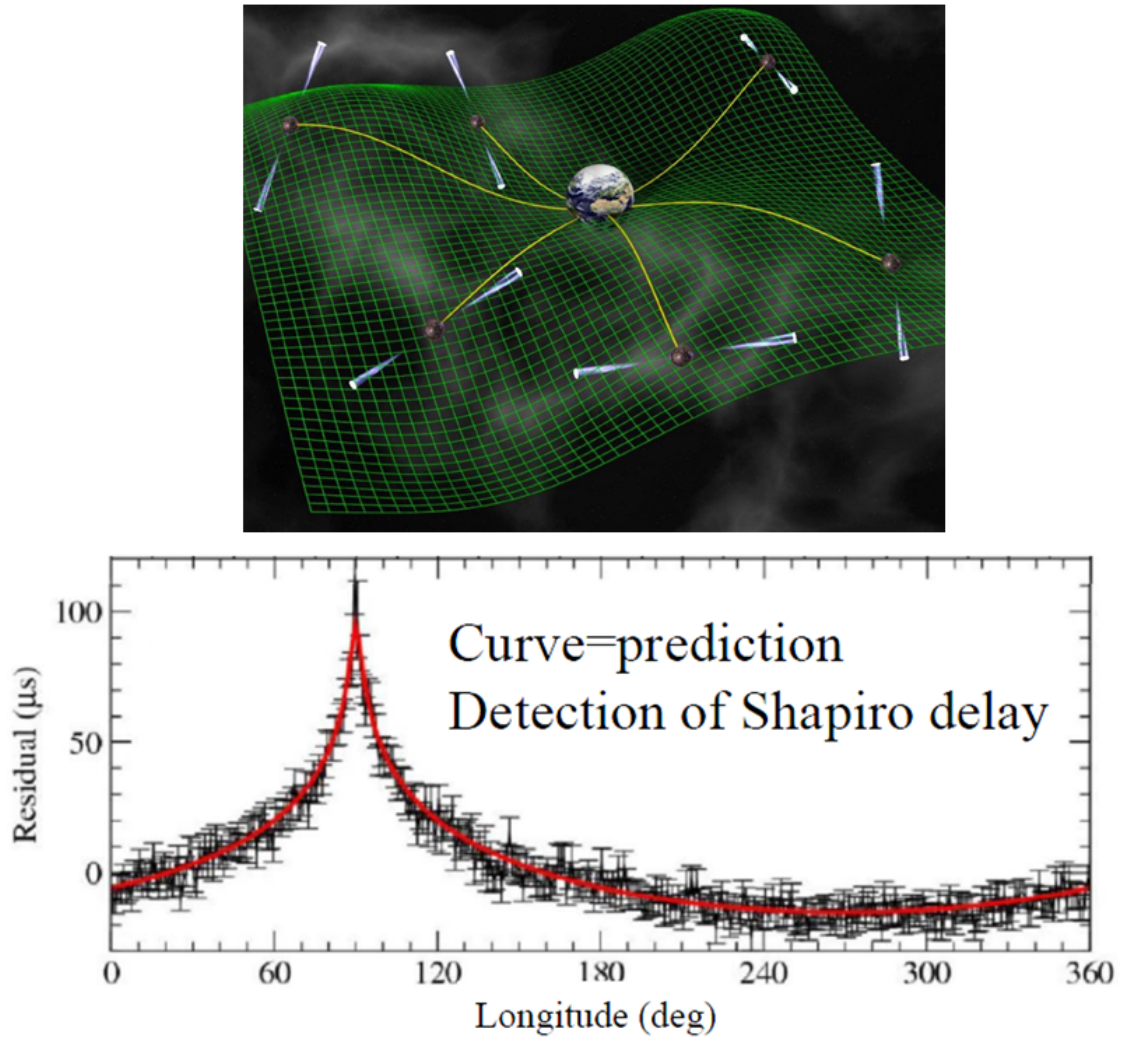
The extreme precision and high sensitivity to be reached by SKA will enable progress in the physics of accreting white dwarfs, neutron stars and black holes, and in general the physics of condensed matter with strong magnetic field. SKA will open and enlarge many domains, as the emission mechanisms of pulsars, nuclear physics and strong interaction, transient phenomena as Rotating Radio Transients (RRAT) or Fast Radio Bursts (FRB), strong field gravity and large-scale structure (Antoniadis et al. 2015).

### 6.1 Timing of pulsars

The MSP J0437-4715, one of the best measured milli-second pulsar, has now (15 July 2014) a period of  $P= 5.7574518589879\text{ms} \pm 1$  in the last digit (13th). This digit increases by 1 every half hour. The neutron star is slowing down due to loss of energy by radiation and emission of a relativistic wind. The first 6 digits will keep the same for  $10^3$  yrs. The time of arrival (TOA) of the signal has been measured with micro-second precision during several years, and that is why a precision of 14 digits is obtained.

Pulsars provide the most precise measures in Astrophysics. For example radial velocities in a binary can be estimated with precision of mm/s, better than the 1m/s precision of exoplanet searches. This can be obtained after one year of astrometric precision on position, and also on spin down, and determining the orbit of the binary (eccentricity, peri-astron, orbital period).

The discovery of thousands or more pulsars will require a lot of data (Cordes et al. 2004). The interstellar medium (ISM) along the line of sight produces a dispersion of the pulses, which arrive with a time delay  $\Delta t$  depending on the frequency  $\Delta t \sim \nu^{-2}$ . Thousands of frequency channels will be observed and delayed, over a 3GHz bandwidth. A discovery implies to sweep over a whole range of dispersions, processing Petabytes of data. A few  $10^4$  trial of dispersion measures



**Figure 4. Top** Schematic reception of the pulsar signals from various regions of the Universe, enabling us to detect the space perturbations, and deduce the passage of gravitational waves. Image credit: David J. Champion. **Bottom** Measurement of the Shapiro delay on the binary pulsar PSR J0737-3039A/B, demonstrating the curvature of space-time. The difference between observed and predicted arrival times for the pulses are plotted as a function of longitude for the pulsar PSR J0737-3039A. The strong peak at  $90^\circ$  longitude corresponds to the position of the pulsar A behind its companion B, so that the pulse experiences a delay when moving through the curved space-time near B. From Kramer et al. (2006).

are required, and a computing power of 0.1 Petaflops. In addition, the de-dispersion is very I/O intensive (Barsdell et al. 2012).

When the binary is edge-on, which is the case of J1614-2230, there must exist a gravitational delay when the MSP passes behind the white dwarf. This is called the Shapiro delay: for an orbit of 8.7 days, the pulses are expected with a delay of  $30 \mu\text{s}$ ! The delay has been observed with the GBT telescope, and the GBT-GUPPI instrument, for which GPU and FPGA are available to process the signal, see figure 4.

## 6.2 Gravitational waves

The extreme precision of the timing of pulsars opens a great opportunity to try to detect gravitational waves, may be even before the specialised instruments, such as LIGO. The principle is to observe and monitor several MSP, and build an equivalent "instrument", the PTA: pulsar timing array (cf figure 4, top). Gravitational waves have nanoHz frequencies (wavelength of  $\sim$  a light-yr). At these time-scales, the correlation between the time of arrival of the signal of the array of pulsars will trace space stretching.

Gravitational waves coming from the merger of black holes, if one occurs nearby, would be detectable at other wavelengths. For the whole of black-hole mergers, since they are at more remote distances, only the noise due to the ensemble of their mergers could be detected as a stochastic background.

Already in the recent years, the number of detected MSP has increased considerably from 10 in 1995 to more than 200 today. Many recent ones were discovered thanks to the Fermi directed radio surveys. With SKA and precursors, there is a bright future for pulsars discovery. The amount of data and beams will be huge, with Terabytes per second. It might be impossible to record everything, and on the fly processing is necessary. Instead of re-analysing data, it will be better to re-observe.

## 6.3 Tests of general relativity

Pulsars measured with extreme precision are the occasion to probe gravity in strong fields. This will be done in binary systems, either a pulsar and a neutron star, or a black hole. The standard gravity law can be checked, and also the cosmic censorship conjecture, that the black hole is a naked singularity, and has no hair, only defined by two quantities, its mass  $M$  and angular momentum  $J$ . The double pulsars timing will yield 0.05% test of general relativity in strong field.

Presently the most precise data comes from the triple system PSR J0337+1715 (Ransom et al. 2014). There is in an inner orbit of 1.6 days a pulsar and a young hot white dwarf of mass  $0.2 M_{\odot}$ , and in an outer orbit of 327 days, a cool old white dwarf of mass  $0.41 M_{\odot}$ . The measurement of all parameters of the system allows to test the Strong Equivalence Principle (SEP), which appears to be verified in strong gravity also, up to now. Other scalar-tensor theories have been constrained (Freire et al. 2012, Antoniadis et al. 2013).

It is expected that 30 000 normal pulsars exist in the Milky Way, and 20 000 will be discovered with SKA, together with  $10^4$  MSP and RRATs (Rotating Radio Transients). The latter have a more irregular cycle but might be more abundant.

## 7. SKA: the instrument

The SKA project, of which a first phase is expected to be operational in 2020, is the project of a giant radiotelescope in the centimetre-metre wavelength range, with one square kilometre collecting surface. This will be 50-100 times more sensitive than present radio telescopes for spectral line observations, and 1000 times more sensitive for continuum observations. The expected range of frequencies is 50 MHz- 25 GHz (or wavelength 1.2 cm- 6m), the field of view from 1 (up to 100) square degrees at  $\lambda$  21 cm / 1.4 GHz, with 8 independent fields of view, or beams, selected within

this area, and angular resolution up to 0.01 arcsec at  $\lambda$  21 cm / 1.4 GHz, obtained with baselines up to  $\sim 3000$  km. The point source sensitivity will be of 10 nano-Jy in 8 hours of integration. The optimal antenna configuration is a dense and compact core, with extended array of antennae disposed in a spiral structure.

At these cm-m wavelengths, the new technology of a wide field of view, allowing to observe with multi-beams several fields of view simultaneously, is a revolution, providing a great efficiency to the observations. Beams are formed electronically, with digital delays, for a fixed network of antennae. The prototype EMBRACE (Electronic MultiBeam Radio Astronomy ConcEpt) is currently tested in Nancay and Westerbork. The LOFAR telescope is presently using similar multibeam technology, and serves as a path-finder for SKA.

SKA is a world-wide project: 55 institutes from 19 countries are participating, 150 scientists and engineers are involved in the project, corresponding at present to more than 100 FTE/year on R&D activities and construction. The total estimated SKA construction cost is about 1.5 billion euros, while the first phase SKA-1 is estimated at 650 millions.

In 2012, two sites have been selected to host the SKA project, Australia and South Africa. The three radio telescopes being built on the two selected SKA sites are called the SKA precursors, they are MWA and ASKAP in Australia, and MeerKAT in South Africa. They have vocation to be included in the final instrument, contrary to the SKA Pathfinders. The latter are facilities or instruments that contribute R&D or other knowledge of direct use to the SKA (e.g., LOFAR).

The foreseen various phases of the different frequency instruments are listed and defined in the table 1. The expected time-scales are:

- 2018 - 2021: construction of SKA1
- 2019/20: early science begins
- 2022- 2025: construction of SKA2
- SKA operational for 50 years.

It is recommended to follow the evolution of the road map on the web site [skatelescope.org](http://skatelescope.org).

## 7.1 Three SKA precursors

SKA precursors are instruments currently built on the two sites of SKA, Australia and South Africa. Two of the instruments (ASKAP and MeerKAT) are concerned with the frequency range 0.7-1.8 GHz, corresponding to HI-21cm up to  $z=1$ , and the third one (MWA) with the low frequency range (80-300 MHz).

MWA, the Murchison Widefield Array in Australia, consists of 2048 dipole antennas arranged as 128 tiles, each 4x4 array of dipoles. The array is fixed, and the beam is formed by electronics only, with a field of view of 25 degrees at 150 MHz. Most of the antennas are within 1.5km, yielding a resolution of a few arcminutes.

ASKAP in Australia is composed of 36 x 12m parabolic antennas, corresponding to a collecting surface of 4000 m<sup>2</sup>. They are equipped by multi-beam Phased Array Feeds (PAF), providing a field-of-view of 30 square degrees. The instantaneous bandwidth is 300 MHz. The instrument is optimised for 30 arcsec resolution.

**Table 1.** SKA Phases 1 and 2<sup>1</sup>

	SKA1-mid	SKA1-low	SKA1-survey
where	Africa	Australia	Australia
telescopes	254 dishes	1024 stations	96 dishes
	64 MeerKAT	array	36 ASKAP
	190 SKA		60 SKA
with respect to	JVLA/meerKat	LOFAR	ASKAP
Sensitivity	6 xJVLA	16xLOFAR	6xASKAP
Survey Speed	74	520	22
	SKA2-mid	SKA2-AA	SKA2-Low
where	Africa	Africa	Australia
telescopes	2500 dishes	Mid-freq aperture array	Low-freq aperture array

<sup>1</sup>Based on numbers before the 2015 re-baselining, which resulted in deferring the SKA1-survey, reducing SKA1-mid to 70% and SKA1-low to 50% of its original size

MeerKAT in South Africa is composed of 64 x 12m parabolic antennas, corresponding to a collecting surface of 7000 m<sup>2</sup>. They are equipped by single-pixel feeds, with a field-of-view of 1 square degree. The instantaneous bandwidth is 1 GHz. The instrument is versatile in spatial resolution, between 6 and 80 arcsec.

For all these instruments, the construction has started, and is expected to be fully operational in 2016-17. The selected design can be seen in figure 5.

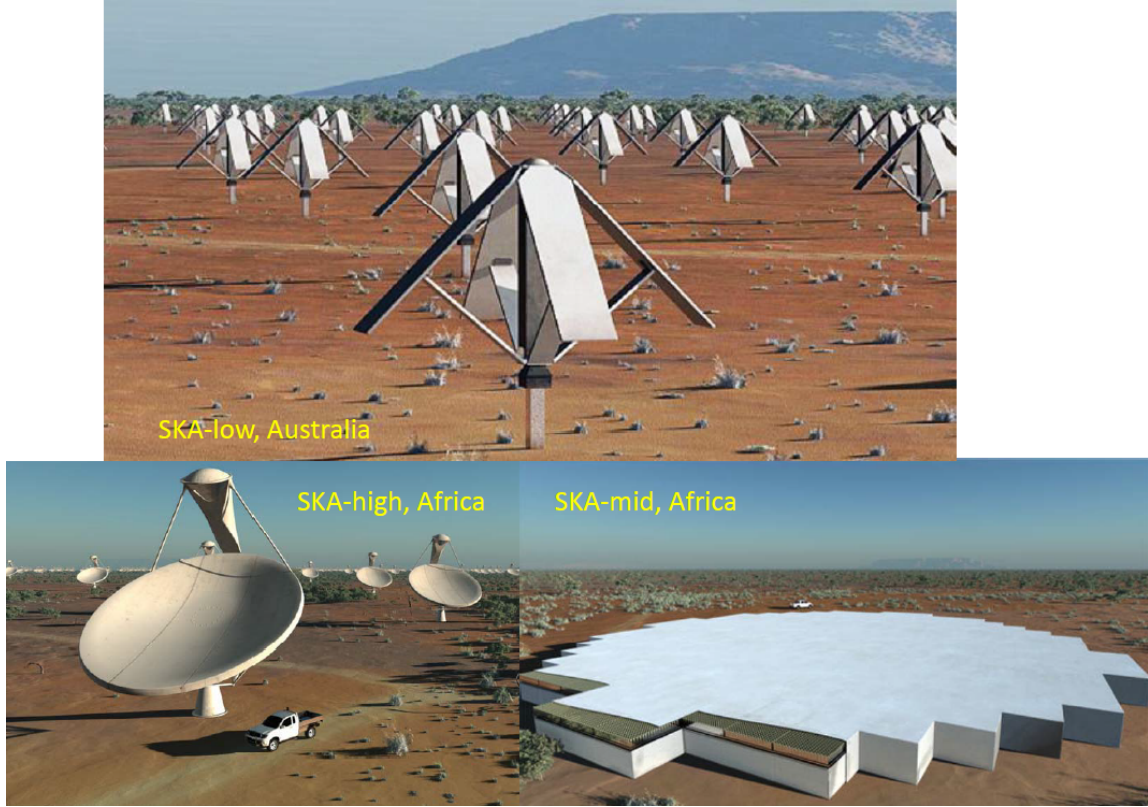
The two higher frequency SKA precursors are very complementary: ASKAP has a large field of view, to make all-sky, relatively shallow surveys, while MeerKAT has a smaller field of view, adapted to deeper surveys, at higher or lower spatial resolution. These can be compared to present instruments in the northern hemisphere. In the Netherlands, Westerbork (WSRT) will be implemented with focal plane arrays (APERTIF), which will increase its field of view by a factor 25. The overlap in the sky with the southern hemisphere precursors concerns the declination range +25°-30°. The VLA, in the USA, can perform deep integration of small field of views, down to -40°. The survey speeds at 0.7 and 1.4 GHz of the SKA precursors are already an order of magnitude larger than that of VLA, and in the SKA-1 phase, they will be 3 orders of magnitude larger. The SKA-2 phase instruments will be 1-2 orders of magnitude faster than SKA-1 instruments.

## 7.2 Data management

The high rate of data acquisition is a huge challenge for SKA. There will be Petabytes per second to process with Petaflops machines working continuously (equivalent to 10<sup>7</sup> personal computers). The data rate, of the order of exabytes per hour, obtained with the dishes corresponds to 10 times the global internet traffic, the data rate with phased arrays is an order of magnitude larger, and is 100 times the world internet traffic!

In comparison, one of the largest data rates for other instruments will be encountered with the LSST (Large Synoptic Survey Telescope), an optical telescope, which will observe the whole sky every 3 days. More than half of the cost is due to the data flow management. The challenge is however much lighter, of the order of 20 Terabytes per night, leading to a total database of





**Figure 5.** **Top** Design of the low-frequency part of the SKA array (to be built in Australia). **Bottom** Design of the high-frequency and mid-frequency parts, to be built in Africa. From skatelescope.org.

60 Petabytes after some years of operation. It will bring however the new dimension of time in focussing on the transient sky, publishing millions of alerts per night for variable objects (stars, supernovae, etc.).

The SKA will open a new frontier in the Big Data science. The exponential growth of the amount of data to process will require new methodologies in data intensive astronomy (e.g. Taylor 2015).

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